231091

UCRL-JC-126840
PREPRINT

Two-Color Infrared Thermometer for Low-Temperature Measurement Using a Hollow Glass Optical Fiber

W. Small, P. M. Celliers, L. B. Da Silva,
D. L. Matthews, and B. A. Stolz

This paper was prepared for submittal to
Society of Photo-Optical Instrumentation Engineers International
Symposium on Optical Applied Science and Engineering
San Jose, California
February 8-14, 1997

February 28, 1997

Lawrence Livermore National Laboratory

Two-color infrared thermometer for low-temperature measurement using a hollow glass optical fiber

Ward Small IV, Peter M. Celliers, Luiz B. Da Silva, Dennis L. Matthews, and Barbara A. Soltz†

Lawrence Livermore National Laboratory, L-399, P.O. Box 808, Livermore, CA 94550
†Conversion Energy Enterprises, #81 Pinebrook Road, Spring Valley, NY 10977

ABSTRACT

A low-temperature fiber optic two-color infrared thermometer has been developed. Radiation from a target is collected via a single 700 μm-bore hollow glass optical fiber coated with a metallic/dielectric layer on the inner surface, simultaneously split into two paths and modulated by a gold-coated reflective chopper, and focused onto two thermoelectrically-cooled mid-infrared HgCdZnTe photoconductors by 128.8 mm-radius gold-coated spherical mirrors. The photoconductors have spectral bandpasses of 2-6 μm and 2-12 μm, respectively. The modulated detector signals are recovered using lock-in amplification. The two signals are calibrated using a blackbody (emissivity equal to 1) of known temperature, and exponential fits are applied to the two resulting voltage versus temperature curves. Using the two calibration equations, a computer algorithm calculates the temperature and emissivity of a target in real time, taking into account reflection of the background radiation field from the target surface.

Keywords: radiation thermometry, infrared, lock-in amplification, blackbody, emissivity, hollow glass waveguide

1. INTRODUCTION

Radiation thermometry is a common non-contact method of measuring temperature. In particular, the technique of two-color pyrometry compensates for the effect of unknown emissivity, which can vary with temperature and surface quality. Two-color pyrometers sample the target radiance in two different spectral regions, and calculate the true temperature and/or emissivity using various algorithms. Many methods of separating the incident radiation into two spectral bands have been used, including using a beamsplitter with two detectors,[1] a rotating filter wheel composed of two different filters with a single detector,[2] and a single detector consisting of two different active regions.[3] Once the radiation is divided into two distinct spectral bands, possible methods of calculation include calibrating the ratio of the two signals[4] which is independent of the emissivity (assuming the emissivity is independent of the wavelength) or solving the two detector response equations simultaneously for the temperature and emissivity.[5] The spectral characteristics of the optical components and the sensitivity of the system determine the useful temperature range of any radiation thermometer.

We have constructed a two-color mid-infrared thermometer incorporating a single hollow glass optical fiber and lock-in amplification for low-temperature measurement. The radiation collected by the hollow glass optical fiber is simultaneously split into two paths and modulated by a reflective optical chopper. Each path contains a detector, whose signal is recovered using lock-in amplification. The temperature and emissivity are calculated in real time from the two detector response equations, taking into account reflection of the background radiation field from the target surface. The mid-infrared spectral bandpass of the system, together with lock-in amplification, enables measurement of the small signals emitted from low-temperature targets.

2. THEORY

2.1. Blackbody radiation

The spectral radiant emittance of a blackbody (emissivity equal to 1) is given by Planck's Law,

$$W_{bb}(\lambda,T) = \frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT}-1} \quad \text{W cm}^{-2}\ \mu\text{m}^{-1}, \tag{1}$$

where h is Planck's constant [6.626×10^{-34} J s], c is the speed of light [2.998×10^{8} m/s], λ is the wavelength [μm], k is Boltzmann's constant [1.381×10^{-23} J/K], and T is the blackbody temperature [K]. Because the spectral distribution is a function of the temperature, the signal produced by a detector that is sensitive to all or part of the radiated thermal spectrum of the blackbody will be related to its temperature.

2.2. Graybody radiation

In the case of a graybody, the emissivity is potentially less than 1 and is independent of wavelength. The spectral radiant emittance of a graybody is related to that of a blackbody (Equation 1) by

$$W(\lambda,\varepsilon,T)=\varepsilon W_{bb}(\lambda,T) \quad \mathrm{W\ cm^{-2}\ \mu m^{-1}}, \tag{2}$$

where ε is the emissivity. If the emissivity is less than 1, the ambient radiation field will be reflected from the target surface and contribute to the detected signal. The detected signal is then given by

$$V(\varepsilon,T_{targ})=\varepsilon V_{bb}(T_{targ})+(1-\varepsilon)V_{bb}(T_{bg}) \quad \mathrm{V}, \tag{3}$$

where V_{bb} is the blackbody temperature response of the detector, T_{targ} is the target temperature, and T_{bg} is the ambient background temperature near the target. The first term represents the contribution from the target and the second term represents the contribution from the reflected ambient radiation field.

Because there are two unknowns in Equation 3, T_{targ} and ε, a second equation is needed to calculate their values. Addition of a second detector with a different spectral bandpass will yield the necessary equation. If both detectors receive the signal from the same area on the target, the geometric dependence is the same for both detector equations and, therefore, does not affect the temperature and emissivity calculation.

3. EXPERIMENTAL SETUP

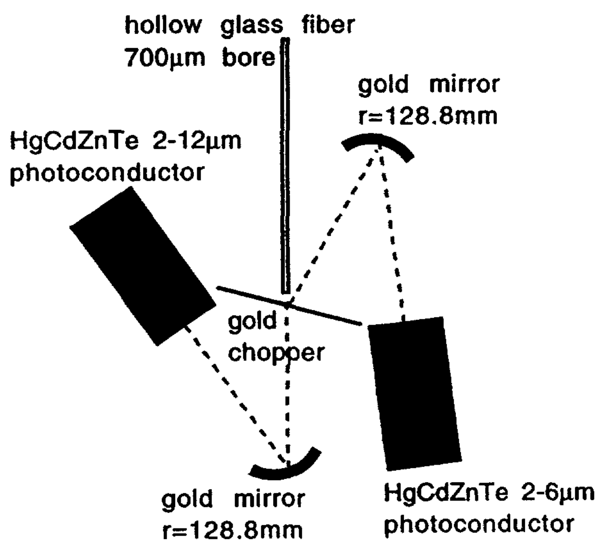

Fig. 1. Configuration of the two-color infrared thermometer. The radiation transmitted by the fiber is either passed or reflected by the chopper, simultaneously modulating the radiation for lock-in amplification and splitting the radiation into two paths.

A 700 μm-bore hollow glass optical fiber coated with a metallic/dielectric layer on its inner surface[6,7] is used to collect the infrared radiation emitted by the target. The numerical aperture of the hollow glass fiber is approximately 0.04, corresponding to a 2° acceptance cone half-angle. The length of the fiber is 2 m. A gold-coated planar chopper is used to modulate the incident radiation while simultaneously splitting the radiation into two paths. Two 128.8 mm-radius gold-coated spherical mirrors focus the radiation onto their corresponding thermoelectrically-cooled HgCdZnTe photoconductors (1x1 mm active area). The spectral bandpasses of the photoconductors are 2-6 μm and 2-12 μm and their response times are <100 ns and <10 ns, respectively. The two modulated signals are recovered using lock-in amplification. A diagram of the configuration of the optical components is shown in Figure 1. The components are contained within a light-tight housing which contains a port through which the hollow glass fiber extends. Also contained within the housing is a thermocouple to monitor the temperature inside the housing. This reading is used to dynamically adjust the two lock-in signals to account for changes in the background radiance. A computer receives the detector and thermocouple signals and calculates the temperature and emissivity using previously obtained blackbody calibration equations.

4. SYSTEM CALIBRATION

4.1. Lock-in signals

Our two-color system measures the radiation intensity in each of the spectral bands using lock-in amplification. The lock-in signals are proportional to the difference between the signals originating from the chopper in the open position and closed position, resulting in a signal that is comprised of target and background contributions. The contribution arising from the background is effectively a constant offset that is independent of the target radiance. Therefore, subtraction of this offset from the measured lock-in signal is required to arrive at the true target signal. It should be noted that this offset is equivalent to the lock-in signal generated by a blackbody target that is sufficiently cold to render the target contribution equal to zero.

4.2. Calibration procedure

The system was calibrated by measuring the lock-in signal of each spectral band as a function of the target temperature using a blackbody target. The blackbody was a 4 x 4 x 4 inch aluminum block with a 1.5 x 1.5 x 1.5 inch hollow cavity in the center. The cavity was formed by removing a 1.5 x 1.5 x 0.75 inch volume from each of two 4 x 4 x 2 aluminum slabs, and joining the two halves together with screws. The joined surfaces were polished to ensure good thermal contact between the two halves. A thermocouple was placed within the aluminum wall to measure the actual temperature. The hollow glass fiber was inserted through a bore in the aluminum wall such that the fiber tip was flush with the cavity edge. The two calibration curves were fit using an exponential function with an additional fit parameter to compensate for the offset in the lock-in signal:

$$V_{\text{lock-in}}(T) = offset + \exp\left(a + \frac{b}{T} + cT\right), \tag{4}$$

where $V_{\text{lock-in}}(T)$ is the lock-in signal [V] and $offset$, a, b, and c are the fit parameters. The calibration curves and their fits are shown in Figure 2. As described above, $offset$ is related to the background radiation field in the system housing, and is governed mainly by the temperature within the housing. It follows that the signal originating from the blackbody only is given by

$$V_{\text{bb}}(T) = V_{\text{lock-in}}(T) - offset = \exp\left(a + \frac{b}{T} + cT\right). \tag{5}$$

Fiber transmittance (which is essentially independent of the wavelength within the measurement band) and system alignment govern a, which is effectively a scaling factor. Prior to using the system, $offset$ and a are finely adjusted by measuring the lock-in signals from a cool blackbody and a warm blackbody, respectively. Because the response of the detectors is relatively flat for cooler temperatures and steeper for warmer temperatures, a cool blackbody is used to adjust the value of $offset$ and a warm blackbody is used to adjust the value of a. Using the original values of a, b, and c, the known cool blackbody temperature, and the measured lock-in voltage, a new value of $offset$ is calculated from the calibration equation. Similarly, a new value of a is calculated using the current $offset$ value, the original values of b and c, the known warm blackbody temperature, and the measured lock-in voltage. The parameters b and c are solely related to the response of the detectors and do not change significantly. These final fits are used to numerically solve for the temperature and emissivity during measurement of target signals.

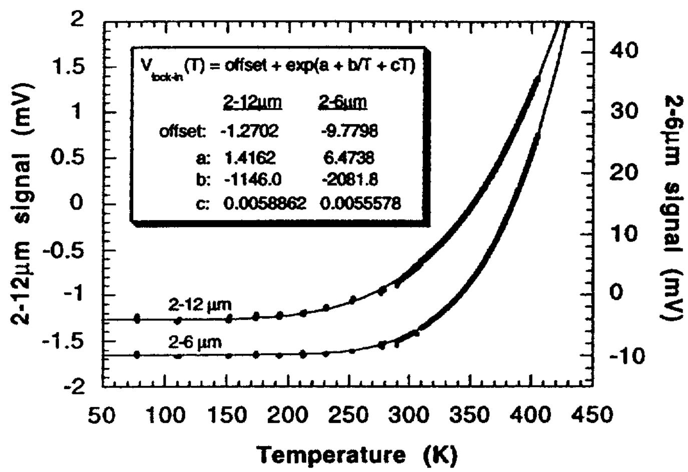

Fig. 2. Detector calibration curves. The lock-in signals from the two detectors were measured as a function of the temperature of a blackbody and were fit with an exponential function.

Variations in the background signal arising from temperature drifts within the housing (i.e., $offset$) are compensated by independently measuring the temperature within the housing (with a thermocouple) and applying temperature dependent corrections to the measured signals. To determine the appropriate corrections, the signals from a target at constant temperature were measured as a function of the background temperature in the housing.

5. CALCULATION OF TEMPERATURE AND EMISSIVITY

Substituting the experimentally determined blackbody temperature response (Equation 5) in Equation 3, the resulting equation for a non-blackbody target is

$$V_{\text{lock-in}}\left(\varepsilon, T_{\text{targ}}\right) - offset = \varepsilon \exp\left(a + \frac{b}{T_{\text{targ}}} + cT_{\text{targ}}\right) + (1-\varepsilon)\exp\left(a + \frac{b}{T_{\text{bg}}} + cT_{\text{bg}}\right). \qquad (6)$$

These two equations, one for each spectral band, can be solved simultaneously for target temperature and emissivity (the background temperature is measured with a thermocouple). However, when $T_{\text{targ}} = T_{\text{bg}}$, no emissivity information is available.

6. MEASUREMENTS

The temperature and emissivity of a blackbody were measured with the two-color system and the calculated temperature was compared with a thermocouple reading (Figure 3). The two-color temperature is in good agreement with the thermocouple reading, and the calculated emissivity is near the actual value of 1.

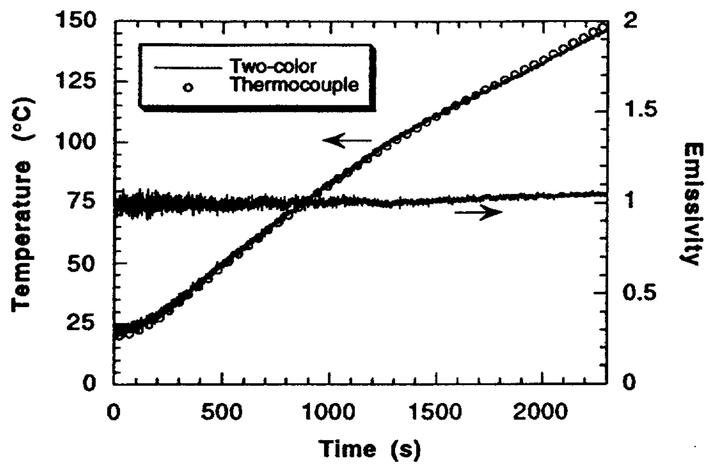

Fig. 3. Temperature and emissivity of a blackbody measured with the two-color infrared thermometer. The same type of blackbody was used for the initial detector calibration (Figure 2), and was used to adjust the offset and scaling parameters at 20°C and 112°C, respectively, prior to the measurement.

Porcine skin coated with a thin layer of an indocyanine green dye (ICG) solution was irradiated with a pulsed 805 nm diode laser at about 2 W (spot diameter = 4 mm). The measured two-color temperature and emissivity histories at the center of the laser spot are shown in Figure 4.

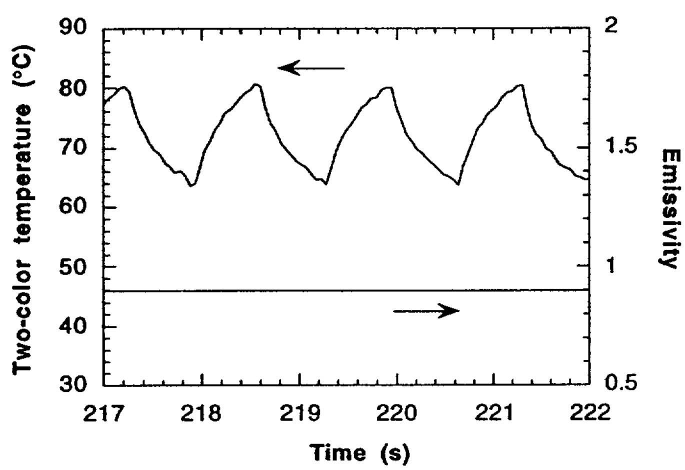

Fig. 4. Two-color temperature and emissivity as a function of time for porcine skin heated with a pulsed laser.

7. SUMMARY

The hollow glass fiber-based two-color infrared thermometer enables dynamic non-contact, fast, high spatial resolution temperature and emissivity measurement. As a result of the two-color principle, the true temperature and emissivity of a target are determined assuming the emissivity is independent of wavelength within the measurement band. Furthermore, correction for reflection of the background radiation field from the target surface enables more precise measurements. Use of a single fiber eliminates the problem of aligning two fibers to a common spot on the target. Because the radiation observed through both bands originates from the same geometric region on the target (which may not be true when a separate fiber is used to collect radiation for each band), the calculated temperature and emissivity are effectively independent of the fiber-to-target distance (for a target of uniform temperature over the observed surface area). The mid-infrared bandpasses of the hollow glass fiber and HgCdZnTe photoconductors, coupled with lock-in amplification, permit measurement of the small signals associated with low-temperature targets.

ACKNOWLEDGMENTS

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-ENG-48 as part of the Cooperative Research and Development Agreement TC-1085-95 with Conversion Energy Enterprises of Spring Valley, New York. The authors wish to thank J. Harrington for providing the hollow glass fiber. Also, the authors wish to thank J. Cox and K. Haney for their help in fabricating the device.

REFERENCES

1. X. Maldague and M. Dufour, "Dual imager and its applications to active vision robot welding, surface inspection, and two-color pyrometry," Opt. Eng. 28(8), 872-880 (1989).
2. K. Crane, *et. al.* "I.R. radiation pyrometer," U.S. Patent #4470710 (1984).
3. O. Eyal and A. Katzir, "Temperature measurements utilizing two-bandpass fiber optic radiometry," Opt. Eng. 34(2), 470-473 (1995).
4. A.S. Tenney, "Radiation Ratio Thermometry," in: *Theory and Practice of Radiation Thermometry*, D.P. Dewitt and G.D. Nutter (eds.), pp. 459-494, John Wiley and Sons, Inc., New York (1988).
5. J. Brownson, K. Gronokowski, and E. Meade, "Two-color Imaging Radiometry for Pyrotechnic Diagnostics," in: *Selected Papers on Temperature Sensing: Optical Methods*, R.D. Lucier (ed.), SPIE Milestone Series 116, 525-532 (1987).
6. T. Abel, J. Hirsch, and J.A. Harrington, "Hollow glass waveguides for broadband infrared transmission," Proc. SPIE 2131, 11-17 (1994).
7. T. Abel, J. Hirsch, and J.A. Harrington, "Hollow glass waveguides for broadband infrared transmission," Opt. Lett. 19, 1034-1036 (1994).